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PATENT APPLICATION ABSTRACT

Predictive Sensor Method and Apparatus

The present invention relates to sensors in general and hydrogen sensors in particular, and is useful in improving the performance of relatively slow responding sensors in situations in which the use of such sensors is indicated but a rapid response is required.

The system of the invention includes a sensor 12 which produces a lagging response to a step change and microprocessor 16 connected to the output of the sensor. The microprocessor samples the sensor output at regular small intervals and uses samples of the sensor output taken at the beginning and end of the current smaple interval to predict the steady state sensor response. Figure 2 compores the predicted sensor steady state output produced by the invention (curve 24) with that produced with a different predictive algorithm (curve 26) and with the raw data (curve 28).

The novelty of the invention appears to be in the use of a predictive algorithm to produce an output representative of the steady state response of a relatively slow responding sensor in situations where such a sensor is needed but a rapid response is required. The invention can be used to upgrade the response of conventional gaseous hydrogen sensors used in monitoring an area in which hydrogen is used as a propellant.

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Print Fig 1

PREDICTIVE SENSOR METHOD AND APPARATUS

Origin of the Invention

The invention described was made by employees of the United States Government and may be manufactured and used by or for the Government for Government purposes without the payment of any royalties thereon or therefor.

Field of the Invention

The present invention relates to sensors of the type which provide a lagging response characteristic and, more particularly, to an improved sensor method and system, employing at least one sensor of this type, for producing an output, in response to an input, which is representative of the ultimate steady state sensor output to that input.

Background Art

Many processes are characterized by a first order process lag, i.e., a first order lag in the response thereof to an input. A general example of such a processes is a sensing process wherein a step input to a sensor does not result in an immediate change in the sensor output corresponding to the change in state represented by the step input. Such a process will impede or delay the function and consequently produce an output response which lags exponentially, before eventually equalizing to the corresponding steady state value. Such measurement lag is obviously undesirable in sensing or detecting systems which are required to quickly and accurately measure changes or perturbations in a process stream.

Condensing a specific application wherein such rapid and high accuracy measurement is required, the extensive use of hydrogen as a propellant in the space program has created a variety of circumstances wherein the presence of hydrogen presents a potential hazard to personnel and equipment. Insofar as applicants are aware, there are currently no commercially available monitoring systems that have been proven to provide a reliable, real-time capability to detect hydrogen in the usual environments encountered by NASA in test, storage and flight operations. In this regard, it should be understood that not only does the hydrogen itself present a hazard, the nature of the hazard is such that the risks associated with the lack of real-time information dictate that some operations be carried out as if hydrogen were actually present. It will be appreciated that the extraordinary operating procedures associated with the handling and use of hydrogen could be relaxed if a reliable hydrogen detection and warning system were available.

Some patents of interest in the general field of gas sensors include: U.S. Patent Nos. 4,587,003 (Tantram); 4,526,028 (Hubner); 4,500,391 (Schmidt); 4,364,810 (Razummey); and 4,069,018 (Karna). Briefly considering these patents, the Tantram patent discloses a gas sensor which produces an output current proportional to thepartial measure of the gas under test. The Hubner patent discloses a process for evaluating environmental parameters such as temperature, pressure and the composition of the atmosphere The reading for a given parameter may be adjusted for correction purposes based on the values of another parameter or parameters, i.e., the readings provided involve interrelated parameters which are jointly evaluated. The Schmidt, et al. patent discloses a gas detection system which provides a more accurate reading of the concentration of a given gas in a test environment by virtue of the measurement of the gas inside of the gas detector device and the superimposition of the signal generated by that measurement onto a signal generated by measuring the partial pressure of the gas directly adjacent to the sensor. The Razummey patent discloses an electrochemical gas detection system which generates a current proportional to the partial pressure of a given gas such a hydrogen. The Karna, et al. patent discloses a system for monitoring an environment for explosive gases wherein, when the level of the explosive gases reaches an unacceptable magnitude, an alarm is activated.

Summary of the Invention

In accordance with the present invention, a measuring or sensing method, and a measurement or sensor apparatus or system, are provided which produce an output corresponding to the actual conditions sensed by a relatively slow responding sensor by predicting the steady state response of the measurement process based on samples of the lagging signal produced by the sensor.

According to one aspect of the invention, a method is provided for improving the response time of a sensor having a relatively slow response characteristic by predicting the steady state response of the sensor, wherein the method comprises: determining the time constant, t_c, of the sensor response; sampling, at small, regular time intervals, the dynamic output measurement signal which is produced by the sensor and which lags the actual conditions sensed by the sensor; and determining the steady state output, V_f, of the sensor by solving the equation:

$$V_f = \frac{V_{i+1} - V_i \exp (\ t/t_c)}{1 - \exp (\ t/t_c \ )}$$

wherein t is the time interval between measurement samples; Vi is the sampled sensor measurement at the beginning of the time interval t; and Vi + i is the sampled sensor measurement at the end of the time interval t.

In a specific application of this method, the sensor comprises a hydrogen gas sensor and the method further comprises employing a plurality of the sensors within an area being monitored for the presence of hydrogen gas.

In accordance with a further aspect of the invention, a sensor apparatus is provided which comprises: a sensor for measuring a predetermined parameter and having a relatively slow measurement response to a perturbation in the parameter being measured; and a microprocessor means, connected to the output of the sensor, for sampling the output of the sensor on regular basis at small sampling intervals, and for producing an output representative of the steady state value of the sensor output based on the sampled outputs of the sensor at the beginning and end of the current sampling interval. The microprocessor means preferably includes means utilizing a predictive algorithm to produce the output representative of the steady state value based on the sampled outputs and the time interval between those sampled outputs. Preferably, the microprocessor means stores a value, t_c, representative of an experimentally determined time constant of the sensor and determines the steady state output, V_f, of the sensor by solving the equation set forth above.

In an advantage application of the invention, a sensor system is provided for determining gaseous hydrogen concentrations in an area being monitored, using at least one hydrogen gas sensor having relatively slow response to changes in the gaseous hydrogen concentration sensed by the sensor, for producing an output proportional to the partial pressure of the gaseous hydrogen sensed thereby. The system produces an output representative of the steady state value of the sensor output based on samples of the sensor output at the beginning and end of a current sample interval, using a microprocessor means, as described above.

In this application, the system advantageously further comprises an alarm activated by the microprocessor means when the output thereof exceeds a predetermined value.

Other features and advantages of the invention will be set forth in, or apparent from, the following detailed description of preferred embodiments of the invention.

Brief Description of the Drawings

Figure 1 is a block diagram of the basic components, and outputs, of a sensor system in accordance with the invention; and Figure 2 is a graph comparing the results produced by the method and apparatus of the invention with the new data produced by the sensor and with the results produced using another predictive algorithm.

Description of the Preferred Embodiments

Referring to Figure 1, and considering the blocks therein which are representative of prior art systems, as discussed above the present invention is a solution to a measurement problem in which the condition being measured, represented by block 10 in Figure 1, and indicated to be a step change in the example being considered, requires the use of a measurement sensor, indicated at 12, which is governed by a lagging process, i.e., which produces an output signal, represented by block 14, in the form of a lagging response, as illustrated. A specific example is the hydrogen sensing process mentioned above. By way of further example, it is noted that catalytic combustion sensors, while providing a relatively rapid response, cannot be used in detecting hydrogen leaks in areas where sufficient oxygen does not exist for proper operation of the sensor. The invention enables the use of a sensor which has a relatively slow (a shown in Figure 1) but otherwise well-behaved response. Such sensors are commercially available and in one example, an electrochemical sensor element, corresponding to sensor 12 of Figure 1, is used which is galvanic in nature and which comprises a diffusion limited platinum black sensing electrode and a metal oxide counter electrode, housed within a polysulfone shell. The electrolyte providing the conductive path between the electrodes is separated from the ambient atmosphere by a gas permeable membrane in intimate contact with the sensing electrode. When the sensor is exposed to hydrogen, a current is generated that is proportional to the partial pressure of the hydrogen present. For a specific electrode configuration, the ratio of the current of the partial pressure is constant at a constant temperature.

Turning now to the present invention, as discussed above, the invention is concerned with producing an output corresponding to the actual conditions by predicting the steady state of the measurement process based on samples of the lagging signal. This is accomplished using microprocessor 16 which, as shown for the specific embodiment under consideration, produces a step output. It will be appreciated that this output can be used in a variety of ways, and as indicated in Figure 1, can be supplied to an alarm device 18, a digital display or other digital device 20, or an analog display 22 or other analog device. The system can also employ plural sensors, as indicated by sensor 12' and sensor output 14', and can process the output of these sensors using microprocessor 16.

Considering the theory of operation of the detection system of Figure 1, it is assumed that the lag which characterizes the output of the sensor 12 can be mathematically described as first order lag. Thus, the dynamic behavior of the process can be described, in accordance with standard process modeling theory (see, e.g., R.H. Perry and C.H. Chilton, <u>Chemical Engineers Handbook</u>, 5th Ed., McGraw-Hill, New York (1973) and W.L. Luyben, <u>Process Modeling, Simulation and Control for Chemical Engineers</u>, McGraw-Hill, New York (1973)), by the following equation:

$$\frac{dv}{dt} = C(V-V_o) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

wherein: V = sensor output;
V_o = initial sensor output;
t = time; and
C = constant

The predicted steady state output of the sensor 12 can, given a set of boundary conditions, be obtained by solving the ordinary differential equation set forth above. Conventionally, the boundary conditions used are: (1) the initial conditions, t_o and V_o, found at the onset of the pertubation in the output of the sensor; and (2) the conditions t_1 and V_1 prevailing at a given instant, and thus the steady state output of the sensor can be represented by the following equation:

$$V_s = \frac{V_i - V_o(\exp(t_o-t_i)/t_c)}{1 - \exp(t_o-t_i)/t_c} \quad \ldots\ldots\ldots (2)$$

wherein: V_s = steady state output of sensor;
V_o = measure of sensor output at present;
V_i = initial output of sensor at onset of pertubation;
t_o = instantaneous time of measurement V_o;
t_i = instantaneous time of measurement V_i; and
t_c = time constant of function

It will be apparent from this equation that a priori knowledge of the conditions V_o and t_o at the onset of the pertubation (see, again, the Perry and Chilton reference and Luyben reference referred to above) is required. Further, the equation is also based on the assumption that the pertubation in the measured condition will be a well defined step function. These characteristics of the equation make such an approach poorly suited to dynamic measurements wherein random step changes occur in the measured quantity.

The approach employed in accordance with the invention uses the following related equation, with real time data being acquired at small, regular intervals:

$$V_f = \frac{V_{i+1} - V_i A}{1-A}, \qquad (3)$$

wherein: A = exp t/t_c and t is the time between measurements;

V_i = the measurement at the beginning of a time interval t; and

V_{i+1} = the measurement at the end of the time interval t.

With this approach, the detection system of the invention characterizes the ongoing dynamic process, thereby continuously solving for the steady state condition.

It will be appreciated from the foregoing that there are a number of important advantages of the invention over prior art methods. More specifically, prediction of the steady state condition relative to a step input is independent of conditions measured in the previous interval. This independence from previous conditions reduces the effects of any higher order of lag exhibited earlier in the process.

Further, as noted above, continuously resetting the boundary conditions make the approach of the invention considerably more suitable for continuous dynamic measurements wherein the process or parameter being measured does not conform to a single well defined step function (such as considered in connection with Figure 1) but rather varies randomly or chaotically. Each measurement made in accordance with the method of the invention results in a new and independent prediction of the unique step function occurring during the measurement interval, with the effect that, when sufficiently small measurement intervals are used, the result is a near instantaneous representation of actual conditions.

A further advantage of the invention is that the detection system can be implemented with common, commercially available electronic components. Moreover, the simplicity of the invention and requirement for a regular sample interval make the invention inherently well suited for digital implementation and application.

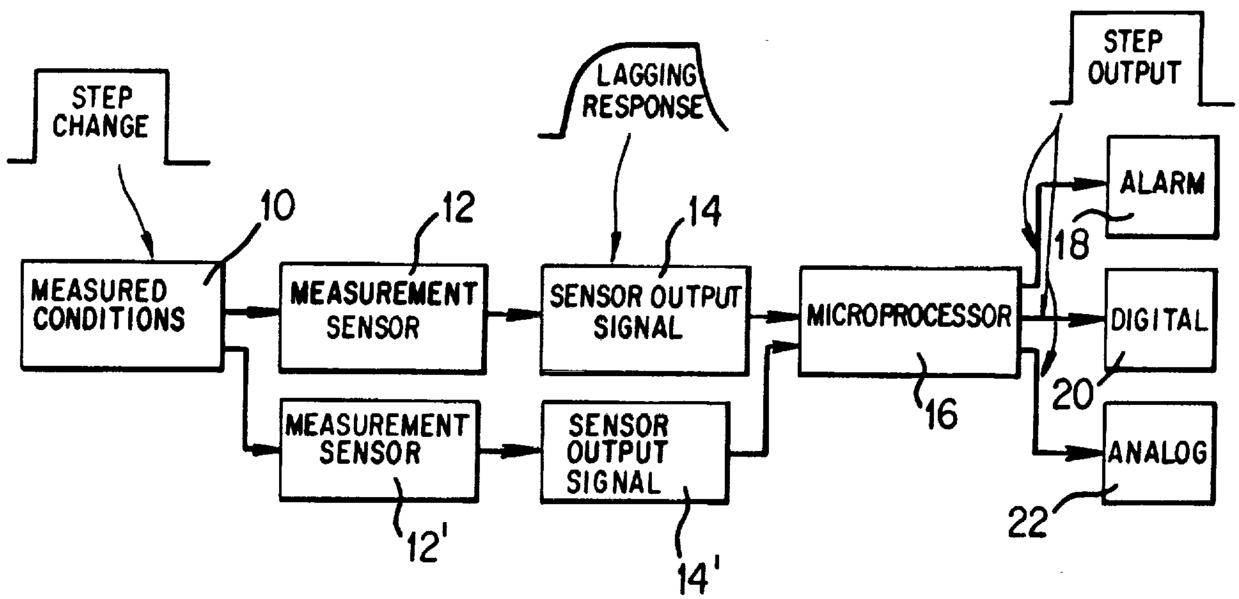
Referring to Figure 2, a plot of sensor or detector response characteristics (per cent hydrogen versus time in seconds) is shown for comparison purposes. More particularly, in Figure 2, the results produced by the present invention are represented by the trace indicated at 24 which is to be compared with the results produced with a method based on the equation (2) above, as indicated at 26, and with the raw data, as indicated at 28. In this example, an electrochemical sensor, corresponding to sensor 12, is used to detect gaseous hydrogen. The specific example involved 0.93% H_2 in air at 98% RH and at a temperature of 31.3 ± 0.3°C. The sensor used employs a special membrane which makes the sensor highly sensitive to hydrogen and essentially insensitive to interfering gases, and which also significantly increases the response time of the sensor to a step change in concentration. As noted above, curve or trace 28 reflects the raw data and, as shown, a time period of approximately 83 seconds is required for the output of the sensor 12 to reach a value equivalent to about 95% of the step input. Similarly, curve 26, as noted above, is based on equation (2) and thus reflects the prediction of the steady state value of the output of the sensor 12 provided by that equation. As shown, the predictive power of the present invention, as reflected by curve or trace 24 and based on equation (3), is substantially greater than that of equation (2), i.e., the present invention significantly improves the response time by discarding all data previous to the small present or current time interval, so that the response produced much more closely tracks the step input or other pertubation.

Although the present invention has been described relative to specific exemplary embodiments thereof, it will be understood by those skilled in the art that variations and modifications can be effected in these exemplary embodiments without departing from the scope and spirit of the invention.

ABSTRACT OF THE DISCLOSURE

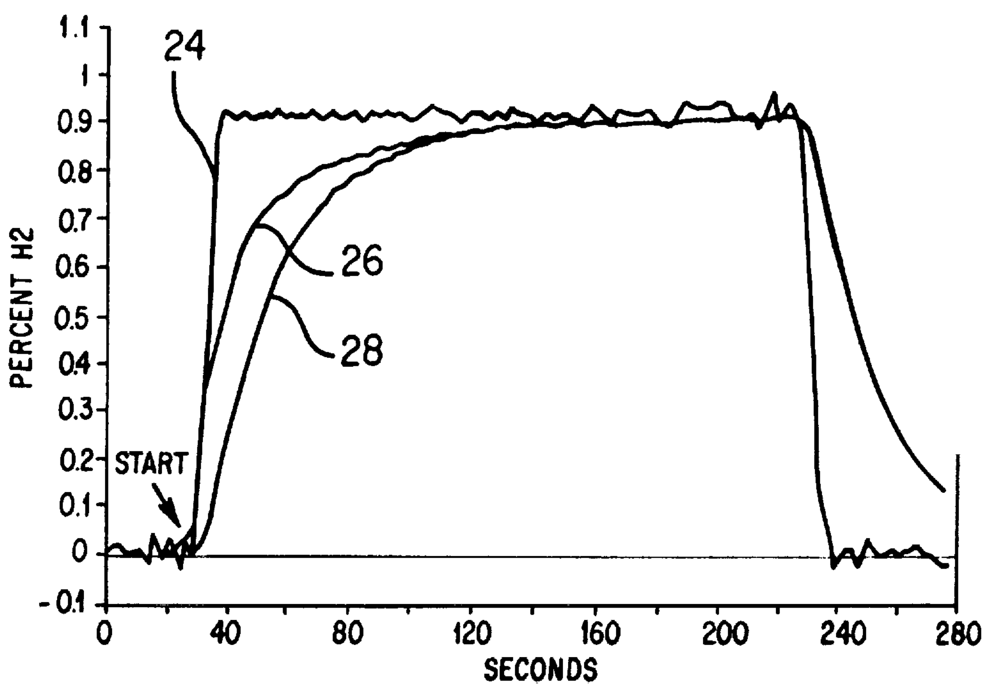
A predictive algorithm is used to determine, in near real time, the steady state response of a slow responding sensor such as hydrogen gas sensor of the type which produces an output current proportional to the partial pressure of the hydrogen present. A microprocessor connected to the sensor samples the sensor output at small regular time intervals and predicts the steady state response of the sensor in response to a pertubation in the parameter being sensed, based on the beginning and end samples of the sensor output for the current sample time interval.

FIG. 1



STEP CHANGE
MEASURED CONDITIONS
10
MEASUREMENT SENSOR
12
MEASUREMENT SENSOR
12'
LAGGING RESPONSE
SENSOR OUTPUT SIGNAL
14
SENSOR OUTPUT SIGNAL
14'
MICROPROCESSOR
16
STEP OUTPUT
ALARM
18
DIGITAL
20
ANALOG
22

FIG. 2



PERCENT H2
SECONDS
START
24
26
28
1.1
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
0
40
80
120
160
200
240
280